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## Higgs dynamics in the early universe

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# Chapter 8

## Summary and outlook

We have explored the phenomenology of the Higgs potential in the early universe. We have seen that a displacement from the zero-temperature vacuum expectation value  $v_0 = 246$  GeV has interesting consequences. We summarize our main findings in this chapter and give an outlook on possible directions for further research.

In chapter 3 we studied the possibility of a negative value of the Higgs self-coupling  $\lambda$  at large energy scales  $\gtrsim 10^{11}$  GeV. A negative self-coupling results in a second minimum in the Higgs potential that is energetically more favorable than the electroweak minimum. Although a non-minimal coupling  $\xi$  between the Higgs field and the Ricci curvature scalar enhances electroweak stability during inflation, this non-minimal coupling leads to very efficient production of Higgs modes during preheating. The EW vacuum gets destabilized for  $\xi \gtrsim 20$ . For  $\xi \lesssim 20$ , particle production is less efficient and no vacuum-independent statements on the fate of the electroweak vacuum can be drawn.

It will be interesting to see whether production of other particles than the Higgs boson can have a stabilizing effect during preheating. So far, Higgs stability has not been studied in a full multi-field context, in the sense that usually only the non-minimal coupling of the Higgs is taken into account. In a more general approach, the non-minimal couplings of the inflaton field as well as the Goldstone modes and possibly additional scalars should be included. For such an analysis, one can use the techniques of chapter 4.

In chapter 4 we assumed  $\lambda > 0$  and studied the production of Higgs modes and gauge bosons after Higgs inflation. We found that gauge boson production is very efficient, but that perturbative decays of the gauge bosons shut off the resonance. Only for  $\xi \gtrsim 1000$  is preheating into gauge bosons successful. The transfer of energy from the Higgs field to the gauge bosons completes within one oscillation. For  $30 \lesssim \xi \lesssim 1000$  reheating proceeds through Higgs self-resonance, which completes approximately 3 e-folds after the end of inflation.

The non-minimal coupling to gravity introduces a UV-cutoff into the theory. Assuming very efficient thermalization, we find that the typical momentum in the thermal spectrum is above the unitarity scale for  $\xi \gtrsim 300$ . A more extensive study of the thermalization stage is needed to indicate more accurately for which values of  $\xi$  the unitarity scale is violated. To understand the behavior of the UV modes, it will be necessary to study preheating in a UV-complete model of Higgs inflation. Furthermore, a comparison to lattice simulations is needed to determine the regime of validity of our linearized analysis. This is work in progress.

It might seem that chapters 3 and 4 are mutually exclusive, since  $\lambda$  is negative in chapter 3 and positive in chapter 4 at the inflationary scale. In Ref. [341] it is argued that, when  $\lambda$  runs negative at some scale  $\mu$ , it may become positive again at a larger energy scale, allowing for Higgs inflation with positive  $\lambda$ . It is shown in Ref. [341] that EW stability is maintained if the reheating temperature is large. It will be interesting to generalize these results in the full multi-field framework of chapter 4, including the non-trivial field-space metric.

In part II we studied electroweak baryogenesis. In chapter 6 we tested the applicability of EFT methods to study EWBG. We came to the conclusion that the requirement of a first-order electroweak phase transition introduces a low cut-off that results in a breakdown of the EFT. This implies that a new light degree of freedom should couple to the Higgs to allow for a first-order phase transition. This conclusion is somewhat disappointing, as we wanted to use the SM-EFT to study EWBG in a model-independent way. Nevertheless, we might learn about the nature of the light degree of freedom via collider experiments. Improved measurements of the Higgs cubic interaction could constrain the light degree of freedom. Another very exciting possibility to probe the first-order phase transition comes from gravitational wave experiments. The LISA experiment that is planned to be launched in the early 2030s can constrain the electroweak phase transition [342, 343].

In chapter 7 we found that the common practice of neglecting the Yukawa interactions of all fermions lighter than the top quarks in the computation of the baryon asymmetry leads to an underestimate of the value of the baryon asymmetry by approximately a factor 4. The enhancement of the asymmetry by the inclusion of lighter fermions is almost exclusively caused by the tau leptons. Furthermore, we showed that a CPV tau source can be more efficient in generating the baryon asymmetry than a top source. We also showed that including an effective lepton-quark interaction might enhance the baryon asymmetry in the case of a CPV top source, but decrease the asymmetry when the source is in the lepton sector. These are interesting considerations that can help model building.

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Throughout part II we have commented several times on the (limited) accuracy of EWBG computations. A big source of uncertainty is the derivation of the relaxation rates and source terms. There are two different formalisms: the semi-classical approximation and the vev-insertion approximation that we have worked with. A thorough comparison of both methods is still lacking. Improvements in the accuracy of the computation of the baryon asymmetry are essential, especially when collider and gravitational wave experiments provide us with more information about the nature of the electroweak phase transition.